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SECONDARY DAMAGE TO AIRCRAFT BY RICOCHETED SMALL ARMS PROJECTILES AND FRAGMENTS

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ABSTRACT

Under certain conditions of oblique impact against aircraft structures, small arms projectiles (or fragments thereof) ricochet, thereby causing damage to adjoining structures, components, or personnel. This report describes terminal ballistics of caliber .30 AP M2 and 7.62-mm ball M59 projectiles striking 0.375-inch-thick 2024-T351 aluminum and 0.25-inch-thick Ti-6Al-4V alloy plates over ranges of obliquity and velocity. Effects of these factors upon potential for secondary damage are assessed. Principles for design of aircraft structures to reduce vulnerability to ricochet damage are proposed.

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INTRODUCTION

Obliquity of impact is a factor affecting vulnerability of structural components to hits by projectiles from small arms, machine guns, and automatic cannon. If obliquity is sufficiently high, the projectiles will ricochet, possibly to strike other components or personnel. Depending upon the nature of and interaction between a metal component and the projectile, the component may eject plugs or back-spall and the projectile may shatter into a number of fragments. This report covers certain experiments designed to assess the damage potential of such secondary particles. The objective of this research was to provide information which could be used for design of aircraft possessing increased survivability against the above threats.

EFFECT OF OBLIQUITY ON ARMOR DESIGN

Under circumstances which restrict the direction of attack by projectile threats, considerable savings in weight can be realized by inclining protective armor plate at an angle oblique* to that direction. The glacis plates of tanks, which are attacked predominantly by projectiles in near-horizontal trajectories from a frontal direction, are inclined in such fashion for this very reason. Ballistic data readily demonstrate that, for a given areal density of armor, the ballistic limit increases with obliquity.[1] Analysis based on these data serves to indicate that disposition of armor plate at 60° obliquity can result in savings exceeding 35% of the weight which would have been required for protection had the plate been positioned perpendicular to the direction of attack, i.e., at 0° obliquity.† Where high obliquities are not compatible with design requirements, benefits of more modest obliquities in the 30° to 40° range remain considerable (see Figure 1).

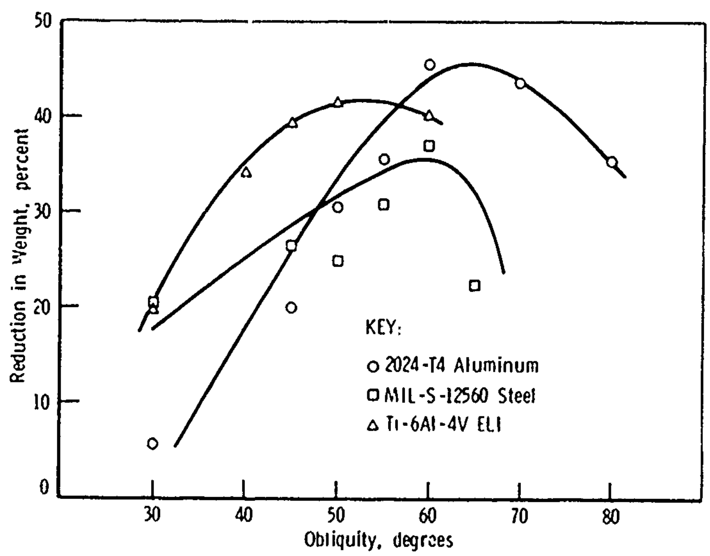

Figure 1. Reduction in armor weight* as a function of obliquity.

*Weight necessary to protect against cal. .50 AP M2 projectiles through a solid angle of incident fire at 500 yards range.

*The angle of obliquity is defined by the shot line and a perpendicular to the plates at point of impact.

†ARNOLD, S. V. *Ballistic Behavior of Armor Under Oblique Impact.* Army Materials and Mechanics Research Center, AMMRC Memorandum, 6 March 1975.

1. MASCIANICA, F. S. *Ballistic Technology of Lightweight Armor - 1976 (U).* Army Materials and Mechanics Research Center, AMMRC TR 76-15, May 1976 (Confidential Report).

BALLISTIC BEHAVIOR OF AIRCRAFT STRUCTURE

Whereas use of parasitic* metallic armor in aircraft is severely limited by the penalty which its weight imposes on performance, some integral armors are more attractive. Aluminum and titanium alloys have well-documented capabilities as armor materials.[1] Obviously, structural members made from these materials behave under ballistic attack in much the same fashion as armor, both in withstanding projectile impact and in shielding other components in the line of fire. Again, obliquity of impact degrades ability for penetration and may result in projectile ricochet. Indeed, if ricochet occurs, the damage potential of ricocheted projectiles (or fragments thereof) varies with obliquity. Vulnerability of components and personnel to such secondary effects can be estimated if direction and energy of ricocheted particles are known.

TEST PROCEDURE

Materials

Panels for ballistic test were sheared from 0.375-inch-thick plate of aluminum 2024 alloy in the T351 condition and from 0.25-inch-thick plate of Ti-6Al-4V alloy in the mill-annealed condition. Areal densities of these plates (intended to be roughly equivalent) were 5.4 and 5.76 pounds per square foot. Square sections were also cut from fiber board to be used in stacks for catching ricocheted projectiles and fragments. The fiber boards, identified as Conwed Rock-Face fire-rated acoustical ceiling panel, were 0.645 inch thick.

Projectiles

The caliber .30 AP M2 round was used for studying terminal ballistics of armor-piercing small arms projectiles. This round has a 166-grain projectile consisting of a copper alloy jacket surrounding an 81-grain hardened steel core.

The 7.62-mm ball M59 round (intended primarily for use against personnel and soft targets) was selected for studying terminal ballistics of a projectile the core of which deforms, rather than fragments. This round has a 150-grain projectile consisting of a copper alloy jacket surrounding a 55-grain soft steel core.

Several fragment-simulating projectiles (FSP) were also employed with calibers and weights as follow: cal. .10 (1.35 grains), cal. .15 (5.85 grains), cal. .22 (17 grains), cal. .30 (44 grains). These projectiles are roughly cylindrical in shape, fashioned from steel and heat treated to a hardness of Rockwell C 30 (see Appendix).

Fixture

A test fixture was constructed of structural channel section for holding (a) the plate to be tested, and (b) a stack of panels positioned to catch projectiles or fragments ricocheting from the plate surface. The fixture and test setup are shown in Figures 2 and 3.

*"Parasitic" armor performs solely in a protective role, as differentiated from "integral" armor which serves simultaneously in protective and structural capacities.

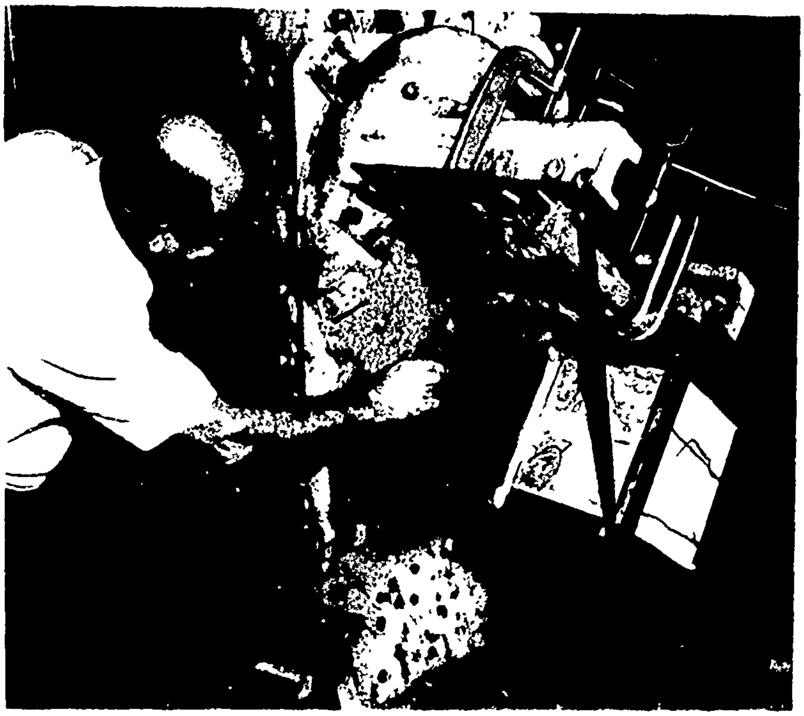

Figure 2. Test setup for ricochet experiment. A cal. .30 AP M2 projectile (following a trajectory in line with the ruler) struck the Ti-6Al-4V plate at 55° obliquity and fragmented. The ricocheting fragments were caught in the upper left corner of the stack (area 10).
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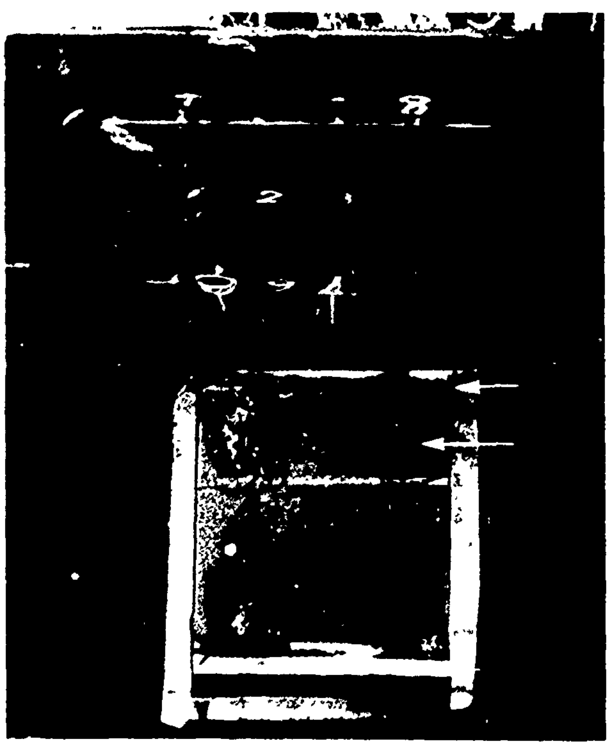

Figure 3. Ricochet setup showing plate impact points 9 and 10 and corresponding areas (below) where ricocheting fragments entered the stack. Note perforations indicating spray of fine fragments close to the plate surface (see arrow), also larger and separate perforations from heavier fragments.

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Test Methods

In the first experiment caliber .30 AP M2 projectiles were fired at 1800, 2200, and 2600 fps velocities to impact the test plate at high obliquities. (These velocities correspond respectively to ranges of 500, 275, and 75 yards for this projectile using the standard charge of powder.) Obliquities were successively reduced until penetration occurred at each velocity. Ricocheted projectiles or fragments were caught in a stack of square panel sections stationed beyond the point of impact in a plane perpendicular to that of the plate (see Figure 2). By changing the point of impact and rotating the stack 180°, ricochet from succeeding shots could be kept separate within the stack. By careful disassembly of the stack, entrapped projectiles/fragments were recovered, their positions relative to the point of impact recorded, and their weight measured. From these data ricochet angle and distance of fragment penetration were calculated. Behavior of fragments other than steel was not analyzed. Steel fragments smaller than 3 grains are not reported herein.

In a second experiment the stack was positioned immediately behind the test plate to entrap projectiles which had completely penetrated the plate. Stack disassembly and recovery of projectiles/fragments enabled measurement of weights and calculation of penetration distances.

In a third experiment various fragment-simulating projectiles were fired into stacks at zero obliquity over a range of velocities. Stack disassembly and projectile recovery was used to establish velocity/penetration relations for the various weights of FSP (see Appendix).

In a fourth experiment 7.62-mm ball M59 projectiles were fired at selected velocities to impact obliquely and to ricochet into a catching stack, as in the first experiment.

DISCUSSION

Terminal Ballistics of Caliber .30 AP M2 Projectiles Impacting Obliquely

Terminal ballistic data are presented in Table 1 for 0.375-inch-thick 2024-T351 and 0.25-inch-thick Ti-6Al-4V plate, both under oblique impact by caliber .30 AP M2 projectiles. Individual shots are itemized to facilitate comparison. Items are listed in order of increasing obliquity and in order of increasing striking velocity within each obliquity grouping. Criterion for complete penetration was perforation of a 0.020-inch-thick aluminum witness sheet positioned 6 inches behind and parallel to the target plate. Whereas distance of fragment penetration through stack panel material was calculated from direct measurements, velocities are estimated on the assumption that projectile fragments behave as do FSP (see Appendix).

Items 1, 2, 4, 5, and 9 present data which give some insight to damage potential of fragments formed which caliber .30 AP M2 projectiles completely penetrate 0.375-inch-thick 2024-T351 plate.

Table 1. TERMINAL BALLISTICS OF CALIBER .30 AP M2 PROJECTILES VERSUS 0.375-INCH-THICK 2024-T351 PLATE (5.4 PSF)

Item	Obliquity (degrees)	Velocity (fps)	Extent of Plate Penetration	Fragment Weight (grains)	Angle of Ricochet (degrees)	Ricochet Stack Penetration (inches)	Ricochet Velocity* (fps)	Behind-Plate Stack Penetration (inches)	Behind-Plate Velocity* (fps)	Remarks
1	30	1847	Complete	35.5	NA	NA	NA	7.2	1540	Nose fragment
1	30	1847	Complete	43.3	NA	NA	NA	5.9	1150	Base fragment
2	40	1674	Complete	35.0	NA	NA	NA	5.2	1040	Nose recovered, base passed through stack
3	40	1818	Complete	-	-	-	-	-	-	Unrecovered+
4	40	1887	Complete	7.6	NA	NA	NA	4.8	1000	Base and smaller fragment traveled together, nose passed through stack
4	40	1887	Complete	27.8	NA	NA	NA	4.8	1000	
5	40	2112	Complete	36.8	NA	NA	NA	8.6	1890	Base fragments, nose lost
6	50	1799	Partial	36.2	21	5.3	1100	NA	NA	Nose fragment
6	50	1799	Partial	43.1	17	5.8	1150	NA	NA	Base fragment
7	50	2104	Partial	-	-	-	-	-	-	Unrecovered+
8	50	2222	Complete	-	-	-	-	-	-	Unrecovered+
9	50	2569	Complete	-	-	-	-	7.8+	1400+	Projectile passed through stack
10	60	1815	Partial	6.6	16	7.9	1750	NA	NA	Base and center fragments which traveled together
10	60	1815	↓	27.6	16	7.9	1750	↓	↓	
10	60	1815	↓	31.6	16	7.2	1500	↓	↓	Nose fragment
11	60	1825	↓	36.4	20	7.2	1520	↓	↓	Base fragment
12	60	2208	↓	31.3	16	7.8	1800	↓	↓	Nose fragment
12	60	2208	↓	47.5	18	7.1	1350	↓	↓	Base fragment
13	60	2632	↓	23.0	27	6.2	1450	↓	↓	Center fragment
13	60	2632	↓	31.4	22	8.4	1950	↓	↓	Nose fragment
14	70	2632	↓	7.0	11	8.4	2600+	↓	↓	Center fragment
14	70	2632	↓	29.2	11	9.0	2180	↓	↓	Nose fragment
14	70	2632	↓	36.5	13	9.6	2150	↓	↓	Base fragment

*Velocity estimated on basis of stack penetration by fragment-simulating projectiles striking at measured velocities.
+Ricocheted projectiles/fragments were not recovered during behind-the-plate studies; projectiles/fragments completely penetrating the plate were not recovered during ricochet studies.

Even at velocities corresponding to ranges of 500 yards and further, complete penetration occurred at obliquities of 30 and 40 degrees. No projectile was recovered intact after complete penetration. The steel core commonly broke into two large fragments corresponding to the nose and base portions, which accounted for nearly all the 81-grain total weight. These large fragments achieved pack penetration sufficient to demonstrate considerable potential for secondary damage. The copper jacket which surrounds the core also passed through the plate and penetrated the stack as highly irregular pieces, which generally traveled shorter distances than the more compact core fragments. Commonly, the projectile pushed out a plug from the aluminum plate which traveled a short distance into the stack.

When obliquity was increased to 50 degrees, the projectile failed to penetrate at a velocity equivalent to 500 yards range (see Item 7) but ricocheted, the core again breaking into two large fragments. At a velocity corresponding to 275 yards complete penetration resulted (see Item 8).

At 60° obliquity, ricochet occurred at all test velocities, i.e., over the spectrum of ranges to be encountered in service (see Items 10 to 13). Many of the larger ricocheted fragments retained nearly all of their striking velocity, i.e., they retained potential for inflicting serious damage to other parts of adjoining structure or components upon which they might impinge.

No reliable correlations between angle of ricochet and striking conditions were noticeable for Items 6, 10 to 14, possibly excepting the fact that lowest angle occurred with highest obliquity.

Table 2. TERMINAL BALLISTICS OF CALIBER .30 AP M2 PROJECTILES VERSUS 0.25-INCH-THICK Ti-6Al-4V PLATE (5.76 PSF)

Item	Obliquity (degrees)	Velocity (fps)	Extent of Plate Penetration	Fragment Weight (grains)	Angle of Ricochet (degrees)	Ricochet Stack Penetration (inches)	Ricochet Velocity* (fps)	Behind-Plate Stack Penetration (inches)	Behind-Plate Velocity† (fps)	Remarks
15	0	1789	Complete	-	NA	NA	NA	7.8+	-	Projectile passed through stack
16	30	1707	Partial	-	-	-	-	-	-	Unrecovered†
17	30	2170	Complete	7.8	NA	NA	NA	3.2	990	Center fragment
18	30	2298	Complete	6.3	NA	NA	NA	5.0	1760	Center fragment
18	30	2298	Complete	27.0	NA	NA	NA	4.3	950	Base fragment
19	30	2595	Complete	6.0	NA	NA	NA	2.0	<800	These are several Ti
19	30	2595	Complete	9.4	NA	NA	NA	2.0	<800	fragments found together
20	40	1748	Complete	-	-	-	-	-	-	Projectile did not penetrate; slight back-spall
21	40	1872	Complete	-	-	-	-	-	-	
22	40	2390	Partial	-	-	-	-	-	-	Back of plate cracked
23	40	2560	Complete	8.5	NA	NA	NA	4.6	1440	Considerable back-spall
23	40	2560	Complete	10.9	NA	NA	NA	5.4	1640	Considerable back-spall
24	45	1790	Partial	4.6	32	0.6	<800	NA	NA	Center fragment
24	45	1790		8.5	23	1.4	<800			Center fragment
24	45	1790		11.5	23	0.7	<800			Center fragment
24	45	1790		13.2	24	2.2	<800			Center fragment
24	45	1790		21.7	23	0.7	<800			Base fragment
25	50	1776		4.1	13	4.0	1490			Center fragment
25	50	1776		9.3	21	4.2	1150			Nose fragment
25	50	1776		59.5	18	2.7	<800			Base fragment
26	50	1802		18.5	21	6.6	1730			Nose fragment
26	50	1802		39.0	0	6.2	1230			Base fragment
27	50	2163		6.0	10	3.6	1100			Center fragment
27	50	2163		16.0	21	6.6	1800			Nose fragment
27	50	2163		39.2	20	4.5	950			Base fragment
28	50	2244	Complete	22.5	10	7.9	2100	-	-	Projectile did not penetrate; slight back-spall
29	55	2187	Partial	5.9	13	3.0	850	NA	NA	Center fragment
29	55	2187		20.8	15	7.0	1180			Nose fragment
29	55	2187		46.5	18	3.0	<800			Base fragment
30	55	2633		4.9	1	4.2	1500			Back of plate cracked
30	55	2633		5.7	17	5.1	1860			Center fragment
30	55	2633		21.0	12	7.7	2050			Nose fragment
30	55	2633		43.5	33	2.8	<800			Base fragment
31	60	1795		26.5	11	7.9	1900			Nose fragment
32	60	1820		23.9	11	6.9	1700			Nose fragment
33	60	2202		3.7	12	6.0	>2600			Nose fragment
33	60	2202		8.2	15	5.0	1580			Nose fragment
33	60	2202		33.0	20	4.2	900			Base fragment
34	60	2627		3.5	23	3.2	<800	NA	NA	Center fragment
34	60	2627		18.6	23	3.2	<800	NA	NA	Base fragment
35	70	2173		28.5	5	7.6	1800	NA	NA	Nose fragment
35	70	2173		31.8	5	8.4	1950	NA	NA	Base fragment
36	70	2578		7.9	2	4.6	1500	NA	NA	Center fragment
36	70	2578		28.6	9	9.5	2450	NA	NA	Nose fragment

*Velocity estimated on basis of stack penetration by fragment-simulating projectiles striking at measured velocities.
†Ricocheted projectiles/fragments were not recovered during behind-the-plate studies, projectiles/fragments completely penetrating the plate were not recovered during ricochet studies.

Items 15 to 23 disclose damage potential of fragments formed when caliber .30 AP M2 projectiles completely penetrate 0.25-inch-thick Ti-6Al-4V plate. Fragments recovered were smaller than was the case for fragments resulting from penetration of 0.375-inch-thick 2024-T351 plate, and their damage potential (judging by stack penetration distances) was less. Copper fragments recovered behind the Ti-6Al-4V plate after complete penetrations were fewer and smaller than in the case of 2024-T351. Penetrations at higher velocities were accompanied by some back-spalling of fragments from the titanium alloy plate (see Items 19 and 23).

At 30° obliquity the projectile failed to penetrate at a velocity corresponding to a range of 550 yards (see Item 16), but did penetrate at velocity corresponding to 300 yards (see Item 17).

At 40° obliquity penetration occurred at velocities corresponding to a 500-yard range (see Items 20, 21). The anomalous result of Item 22 is not understood.

At obliquities of 45 degrees and higher ricochet occurred at velocities equal to or greater than those corresponding to a 500-yard range. The projectiles broke into small fragments of limited damage potential (see Item 24).

At 50° obliquity ricochet occurred over a number of increasing velocities until a limit corresponding to 275 yards was reached (see Items 25 to 29) at which penetration occurred.

At obliquities of 55 degrees and greater, ricochet (rather than penetration) occurred over the velocity spectrum to be encountered in service.

Inspection of ricochet data for Ti-6Al-4V/caliber .30 AP M2 show at 1800-fps striking velocity the average ricochet angle decreased progressively 25°, 15°, and 11° for increasing obliquities of 45°, 50°, and 60°, respectively. At 2200 fps average ricochet angles of 15°, 15°, 18°, and 5° were realized for obliquities of 50°, 55°, 60°, and 70°, respectively. At 2600 fps, average ricochet angles of 15°, 23°, and 5° were realized for obliquities of 55°, 60°, and 70°, respectively. At obliquities of 50°, 55°, and 70° increased striking velocity had no effect on ricochet angle; at 60°, however, this was not the case.

It should be remarked that, whereas the above discussion refers to "average" ricochet angles of projectiles fragments, this so-called average applies only to those *steel* fragments which were recovered and recorded. Generally, fragments less than several grains in weight were not recorded. Observation of the fragment pattern on the stacked panel (see Figure 3) showed that many small fragments fanned out from the point of impact closely parallel to the plate surface. The larger steel fragments, which were recovered and recorded for assessment of damage potential, ricocheted at greater angles to the plate. In no instance did the angle of ricochet (reflection) equal the angle of incidence (90° minus angle of obliquity), however.

Whereas ricochet angle has been reported within a plane defined by the original trajectory and a line perpendicular to the plate surface, some lateral deviation from this plane was observed. For the larger steel fragments recorded the angle of such deviation was no more than several degrees. Copper fragments from the jacket deviated laterally more than the larger steel fragments.

Since some differences in penetration and ricochet behavior depended on plate material, comparison of potential for secondary damage by fragments was undertaken through analysis of 2024-T351 and Ti-6Al-4V data. Because similar obliquity/velocity combinations were lacking, comparison of damage potential of fragments after plate penetration was not possible. (However, as noted previously, weights of individual steel fragments recovered after complete penetration of 0.375-inch-thick 2024-T351 plate were greater than those recovered after complete penetration of 0.25-inch-thick Ti-6Al-4V plate.) Several sets of similar data were available for comparison of ricocheted fragment damage potential (see Table 3). Within a given set, fragments of equivalent weight usually penetrated like distances, but more heavier fragments were recovered after ricochet from 2024-T351.

Secondary Damage by Fragments

The concept of secondary damage requires some examination. Since vulnerability of various unspecified aircraft components is involved, one may only project ways whereby fragments could inflict damage.

Fragments may penetrate instruments and other software rendering the device inoperable. Fragments may completely or partially sever small structural elements (e.g., wires, cables, stringer, etc.).

Table 3. DAMAGE POTENTIAL OF RICOCHETED FRAGMENTS: EFFECT OF PLATE MATERIAL

Item Ti*	Item Al†	Obliquity (degrees)	Velocity (fps)	Fragment Weight (grains)	Penetration‡ Distance (inches)
	6	50	1799	36.2	5.3
	6	50	1799	43.1	5.8
25		50	1776	4.1	4.0
25		50	1776	9.3	4.2
25		50	1776	59.5	2.7
26		50	1802	18.5	6.6
26		50	1802	39.0	6.2
	10	60	1815	6.6	7.9
	10	60	1815	27.6	7.9
	10	60	1815	31.6	7.2
	11	60	1825	36.4	7.2
32		60	1795	26.5	7.9
33		60	1820	23.9	6.9
	12	60	2208	31.3	7.8
	12	60	2208	47.5	7.1
34		60	2202	3.7	6.0
34		60	2202	8.2	5.0
34		60	2202	33.0	4.2
	13	60	2632	23.0	6.2
	13	60	2632	31.4	8.4
35		60	2627	3.5	3.2
35		60	2627	18.6	3.2
	14	70	2632	7.0	8.4
	14	70	2632	29.2	9.0
	14	70	2632	36.5	9.6
37		70	2578	7.9	4.6
37		70	2578	28.6	9.5

*0.25-inch-thick Ti-6Al-4V plate
†0.375-inch-thick 2024-T351 plate
‡Penetration into stacked panel board

Sections of more massive elements may be partially penetrated. In some instances, the mechanical defect in combination with service loads may cause immediate failure or promote fatigue failure at some later time. At a given ricochet (or post-penetration) velocity, a heavier fragment will make a more serious defect because (1) it is larger, and (2) unless ricocheting itself, it will penetrate further.

Perforation of tubes, sumps, tanks, etc., is another means for secondary damage. At a given velocity, larger fragments have a greater chance for complete penetration and, by making a larger hole, will expedite depletion of the stored liquid or gas. These effects may involve engine operations and/or fire hazard. The ability of fragments to perforate (completely penetrate) various thicknesses of structural metals and fiber-reinforced plastic can be judged, if one assumes they behave as do fragment-simulating projectiles for which a body of data has been published (see Appendix). The assumption is considered reasonable for instances where fragments possess density, shape, and deformability approximating that of FSP's. On the basis of such assumption it is evident that fragments of caliber .30 AP M2 projectiles, either ricocheted or post-penetration, commonly possess secondary damage potential such that they will be capable of penetrating completely a 0.10-inch-thick sheet of Ti-6Al-4V, a 0.20-inch-thick panel of glass-fiber-reinforced plastic (GFRP), or 0.25-inch-thick plate of 2024-T4 (see Table 1 and Figure 4).

This study of ricochet and post-penetration fragments from caliber .30 AP M2 projectiles provides the aircraft designer with information bearing upon materials selection, modes of construction, and component disposition within the aircraft.

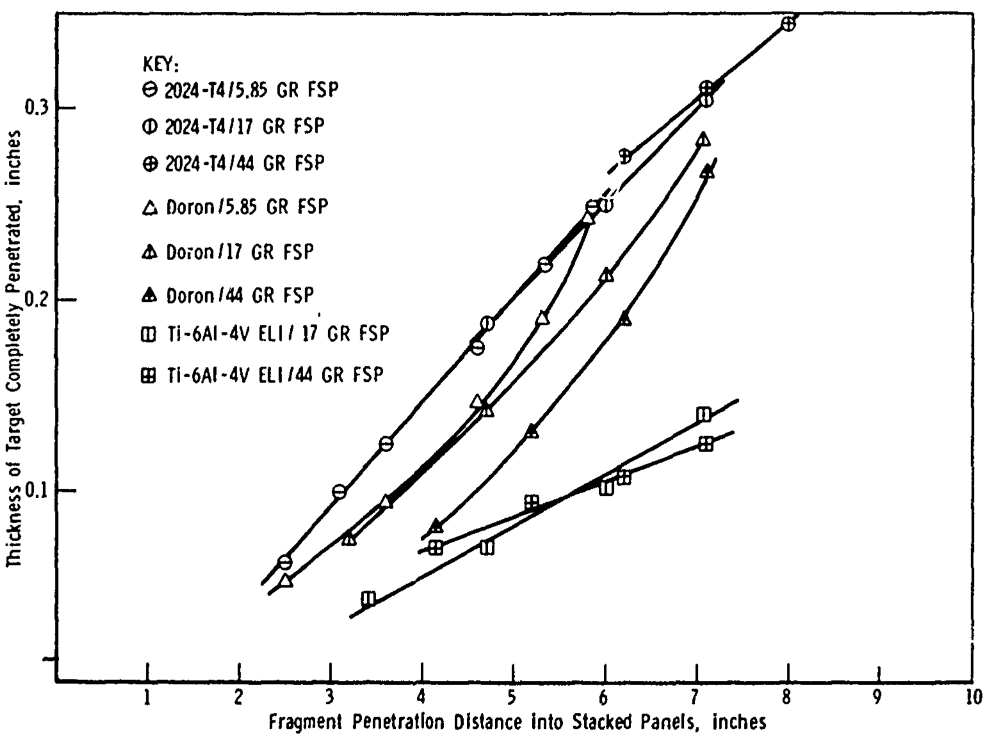

Figure 4. Comparison of materials penetration by FSP's at equivalent velocities.

Harder structural materials (e.g., steel and titanium alloys) promote greater fragmentation of impinging steel armor-piercing cores than do softer materials (aluminum alloys, GFRP). Since at a given velocity smaller fragments individually possess lower damage potentials, the designer may elect to promote fragmentation and provide adequate tolerance in surrounding components/structure; or, conversely, he may suppress fragmentation in order to reduce the number of secondary targets which will be struck.

Terminal Ballistics of 7.62-MM Ball M59 Projectiles Impacting Obliquely

If projectiles ricochet without fragmenting, their damage potentials are greater corresponding to their weight (see Table 4). The 7.62-mm ball M59 projectile consists of a soft 55-grain steel core within a copper jacket. When this projectile ricocheted from 0.375-inch-thick 2024-T351 plate, the core deformed to a banana shape (see Figure 5), but did not shatter. When impacting at 50 to 60° obliquity, this projectile ricocheted at low angles. As striking velocity increased, the projectile dug deeper into the plate and then ricocheted at reduced velocity. Item 43 records an instance where the projectile ricocheted from the forward face of the plate while its impact ejected an aluminum plug from the rear face, leaving a sizeable hole.

When the 7.62-mm ball M59 projectile struck Ti-6Al-4V plate at obliquity of 50 to 60°, there was no penetration or observable plate deformation over the range of velocities to be encountered in service. At points of impact the plate surface was smeared with copper and iron, the appearance at low magnification suggesting that instantaneous melting had occurred. The projectile cores were flattened on one side with a banana curvature (see Figure 5). It was observed that the weight of cores recovered from projectiles impacting at 50 degrees was reduced several tenths of a grain, presumably from erosion/alloying during impact. Since molten metal seems to have been formed and ejected, possibility of incendiary action is postulated.

Again, a low order of ricochet angle was observed for both plate materials and both obliquities.

Table 4. TERMINAL BALLISTICS OF 7.62-MM BALL M59 PROJECTILES VERSUS Ti-6Al-4V AND 2024-T351 PLATES*

Item		Obliquity (degrees)	Velocity (fps)	Extent of Plate Penetration	Fragment Weight† (grains)	Angle of Ricochet (degrees)	Ricochet Stack Penetration (inches)	Remarks
0.375-inch-thick	40	50	1842	Partial	53.6	5	6.2	
2024-T351 plate	41	60	1847	Partial	53.6	8	8.9	
	42	60	2196	Partial	53 6	5	8.1	
	43	60	2585	Complete	53.6	5	6.8	Projectile ricocheted, plug ejected from rear face of plate
0.25-inch-thick	44	50	1704	Partial	53.2	5	9.8	
Ti-6Al-4V plate	45	50	1794	↓	53.1	13	10.1	
	46	50	2223	↓	53.4	10	10.9	
	47	60	1830	↓	53.5	8	11.5	
	48	60	2223	↓	53.6	6	11.7	
	49	60	2623	↓	53.7	6	13.1+	Projectile would have passed through stack but was blocked at rear face

*0.25-inch-thick annealed Ti-6Al-4V (5.76 psf) and 0.375-inch-thick 2024-T351 (5.4 psf).
†Soft steel cores of M59 projectiles distorted on impact, but remained intact.

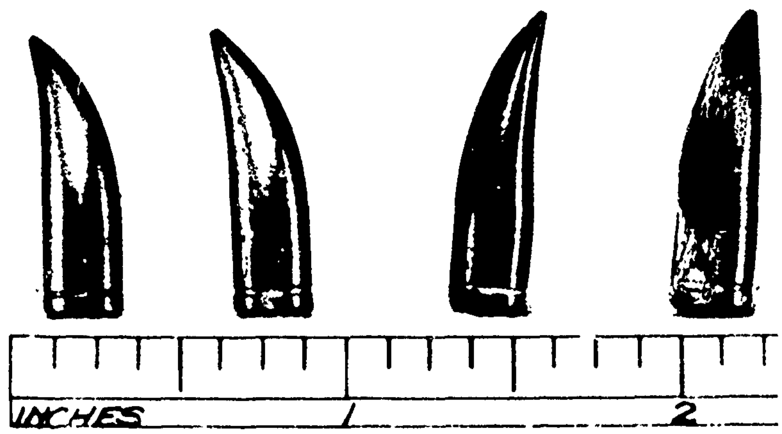

Figure 5. Steel cores from 7.62-mm ball M59 projectile, bent by ricochet from 2024-T351 aluminum plate (left), bent and flattened by ricochet from Ti-6Al- 4V plate (right).
19-066-364/AMC-76

Attempts to estimate core ricochet velocities on the basis of FSP penetration data resulted in anomalously high values which were attributed to the difference in shape between the deformed cores and the FSP's.

Comparing damage potential (stacked panel penetration) of ricocheted 7.62-mm ball M59 cores as a function of target plate material, plate impact velocity and obliquity reveals significant differences (see Figure 6). Damage potential of ricocheted cores from projectiles striking 0.375-inch-thick 2024-T351 plate at 60° obliquity *decreased* with impact velocity, whereas the damage potential of cores ricocheted from like projectiles striking 0.25-inch-thick Ti-6Al-4V plate at 50° and 60° obliquities *increased* with impact velocity. The reason for this difference is apparent when plate penetration of the two materials is compared: the aluminum alloy plate sustained greater damage as impact velocity increased, but absorbed more of the projectile's energy; by contrast, the titanium alloy plate was neither penetrated nor deformed by projectile impact and higher impact velocities translated unreduced to higher ricochet velocities, i.e., greater damage potential of the ricocheted core. Examination of stack penetration distances for comparable items (41 versus 47, 42 versus 48, 43 versus 49) indicates that damage potentials of cores ricocheted from the Ti-6Al-4V plate exceeded those of cores ricocheted from 2024-T351 by 29 to 93+ percent.

The above observations and findings have several connotations for aircraft design. Structural elements fashioned from Ti-6Al-4V with sections 0.25 inch thick or greater will not be damaged by 7.62-mm ball M59 projectiles striking under service conditions which result in ricochet, whereas elements fashioned from 2024-T351 with sections 0.375 inch thick or greater will be deformed and/or partially penetrated.

If structural elements fashioned from 2024-T351 can tolerate the damage imparted by 7.62-mm ball M59 projectiles striking at obliquity (i.e., the structure or component remains functional), cores ricocheting from such structural elements will possess substantially less potential for inflicting secondary damage than would be the case if the structural elements were fashioned of Ti-6Al-4V. This behavior should also be considered in armor applications where secondary damage to adjoining personnel/structure by ricocheted ball projectiles is a factor.

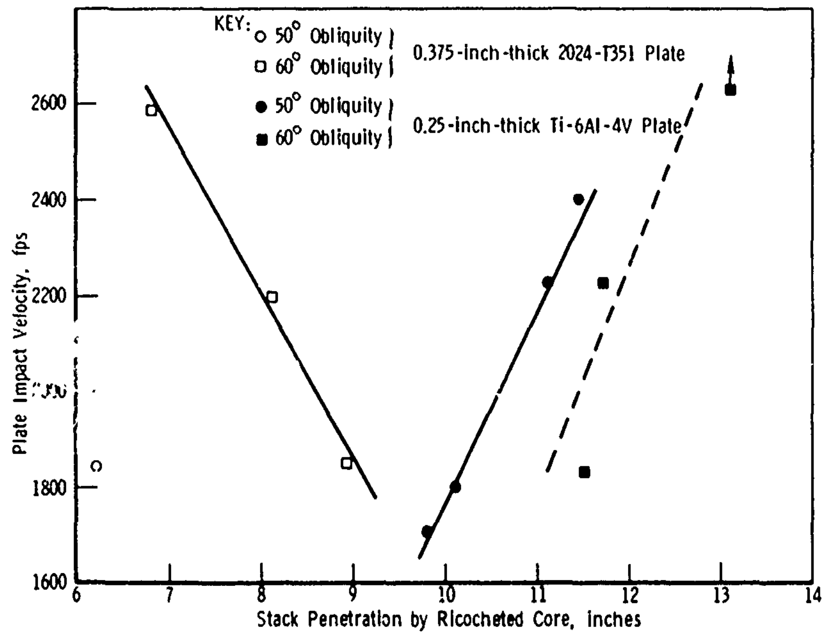

Figure 6. Effect of target material, impact velocity and obliquity on damage potential of ricocheted cores from 7.62-mm ball M59 projectiles.

If steel fragments from high explosive shell and SAM warheads ricochet at lower velocities from aluminum than from titanium structure (as would be expected on the basis of 7.62-mm ball M59 core ricochet data), materials selection will also influence vulnerability of aircraft structure and components to secondary damage from fragmenting threats.

Aircraft Design for Reduced Vulnerability

For like conditions of impact velocity and obliquity, cores of 7.62-mm ball M59 projectile ricochet intact and possess higher potentials for secondary damage than do ricocheting fragments of cores from caliber .30 AP M2 projectiles, fragments which, on the average, weigh considerably less than the intact core. However, on a per-round basis, a greater number of secondary targets is likely to be struck by the fragments. If a secondary target is soft, a fragment's damage potential may suffice to render it inoperative. Aircraft designers not infrequently surround critical components with less vital parts in order to reduce the likelihood that the former will be struck by threat projectiles. This stratagem may not work, if the critical component remains vulnerable to ricocheted or post-penetration cores or fragments.

If a system will be exposed to a projectile threat only from a certain direction, designers may use this circumstance to advantage. There has, for example, been no requirement to protect helicopters from small arms fire originating from above. Similarly, if the direction of incident fire is known, or can be restricted (as by shielding), it may be possible to design and position a component in such a way as to maximize ballistic tolerance without suffering a weight/performance penalty. Housings, for example, could be constructed of materials which resist penetration, and with surfaces inclined so that the preponderance of incident small arms projectiles would strike at obliquity and ricochet. (To provide such tolerance for a multidirectional threat would require heavier wall sections and impose some weight penalty.) Continuing this line of reasoning, if both threat direction and obliquity of impact are known, ricochet of fragments can be predicted and appropriate measures taken to relocate or protect soft parts susceptible to secondary damage.

CONCLUSIONS

1. When caliber .30 AP M2 projectiles struck 0.375-inch-thick 2024-T351 plate at velocities corresponding to 500 yards range or less, and at test obliquities of 30 to 70°, the hardened steel core broke, whether in ricochet or during penetration, so that two large fragments remained, comprising most of the core weight. In both the ricochet or post-penetration modes these steel fragments possessed potential for substantial secondary damage. During complete penetration a plug of aluminum was ejected from the rear surface of the plate and copper fragments from the jacket carried through with the core.

2. When caliber .30 AP M2 projectiles struck 0.25-inch-thick Ti-6Al-4V plate under similar test conditions to the above, core breakage again occurred and the extent of fragmentation was greater, i.e., a larger number of smaller fragments was generated, but some larger fragments remained. Relatively few jacket fragments passed through the plate during complete penetration. Back-spall commonly occurred during complete penetrations.

3. For ricocheted fragments generated under similar test conditions of velocity and obliquity of impact, those of like weight penetrated stacked panel material to roughly equivalent distances. Penetration distance was taken to be a measure of damage potential. Using fragment-simulating projectiles fired directly into a stacked panel at 0° obliquity, a correlation between penetration distance and striking velocity was established. Assuming similar penetration behavior for core fragments from caliber .30 AP M2 projectiles, damage potential of fragments was rated in terms of ability to penetrate completely various thicknesses of 2024-T4 plate, Ti-6Al-4V sheet, and glass-fiber-reinforced plastic.

4. Selection of materials for those components directly exposed to incident fire can affect fragmentation of armor-piercing cores. Materials which promote fragmentation result in more but smaller fragments, the individual damage potential of which is less than that of larger fragments, assuming like velocities. In circumstances where the vulnerable area of soft parts exposed to ricochet is small, materials which favor a minimum number of fragments may be preferred in order to reduce probability of a hit.

5. The angle of ricochet for fragments of caliber .30 AP M2 projectiles was shown to be appreciably less than the angle of incidence (90° minus angle of obliquity). Small fragments fanned out from the point of impact close to the plate surface, while larger fragments ricocheted at somewhat greater angles. Angles of fragment ricochet were least at the highest obliquity, 70 degrees. Lateral deviation of larger fragments from the original trajectory was only a few degrees.

6. When 7.62-mm ball M59 projectiles struck 0.375-inch-thick 2024-T351 and 0.25-inch-thick Ti-6Al-4V plate at velocities corresponding to 500 yards range or less, the soft steel cores deformed but did not fragment. As striking velocity increased, the aluminum alloy plate was indented more severely and damage potential of the ricocheted core decreased. The Ti-6Al-4V plate was neither deformed nor indented by these cores. The damage potential of M59 cores ricocheting from the titanium plate increased both with striking velocity and with obliquity. This behavior indicates an inverse relation of primary to secondary damage where ricochet of soft steel projectile cores is concerned. This relation may also apply to steel fragments from high explosive shell/warheads. A degree of control as regards this inverse relation can be achieved through selection of structural materials.

7. Options for reducing aircraft vulnerability to secondary damage from ricocheted projectile cores and fragments include design and positioning of components. Under circumstances where ricochet trajectories are limited, the designer has the choice of (1) designing the component to defeat the ricochet or tolerate such damage as it may inflict; otherwise, (2) he may elect to position the component in a less hazardous location.

ACKNOWLEDGMENT

This will express the authors' gratitude to personnel of Ballistic Test Range for their ready cooperation during conduct of the subject investigation, in particular to Mr. Salvatore Favuzza whose interest and technical assistance were most helpful.

APPENDIX. STACK PENETRATION BY FRAGMENT-SIMULATING PROJECTILES

The damage potential of fragments from high-explosive ammunition has long been a matter of concern to designers of weapon systems. Such fragments vary over a wide range of weight and shape depending upon the shell, bomb, or other device from which they derive. Certain munitions have been developed to release fragments of a weight optimal for antipersonnel use. Studies, both to determine optimal antipersonnel fragment weight and, conversely, to evaluate personnel armor providing protection against such fragments, have been facilitated through use of fragment-simulating projectiles (FSP) which can be fired under reproducible test conditions against selected targets.

One design of FSP extensively used in personnel armor development at AMMRC is shown in Figure A-1. This design was adopted in the subject program. It is produced in a number of standard weights over the range 1.35 to 830 grains. The smaller simulators, 1.35, 2.65, and 5.85 grains, are mounted singly in plastic sabots and fired from a caliber .22 gun. All others are fired (without sabots) from standard rifled gun tubes: e.g., 17 gr/cal. .22, 44 gr/cal. .30, etc. These FSP's are fashioned from steel heat treated to Rockwell C 30 ± 2 hardness (which is the average hardness of fragments recovered from domestic 105-mm HE shell).

In the subject program penetration of stacked panel sections by 5.85-, 17-, and 44-grain FSP's fired over a range of velocities was used to assess the ballistic behavior of the *panel material* (see page 2 of the report). Stack penetration data for selected FSP's are listed in Table A-1 and plotted as a function of striking velocity in Figure A-2. Using interpolated values from Figure A-2, curves relating stacked panel penetration and fragment weight at 200 fps velocity intervals over the range 800 to 2600 fps were constructed, see Figure A-3. Using curves in Figure A-3 and curves depicting FSP behavior against various materials previously published,[1] it was possible to equate (a) stacked panel penetration with (b) material thickness completely penetrated for several weights of FSP striking at equivalent velocities (see Figure 4 in body of this report).

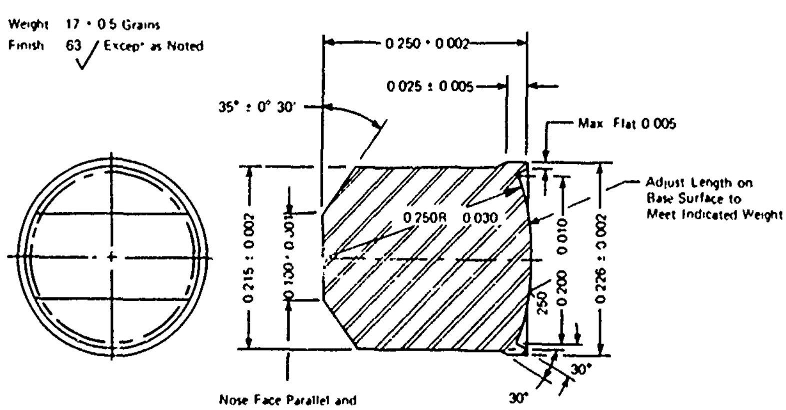

Figure A-1. Fragment-simulating projectile, 17 grain/caliber .22.

Table A-1. STACK PENETRATION BY FRAGMENT-SIMULATING PROJECTILES*

Projectile Weight (grains)	Velocity (fps)	Penetration (inches)
5.85	631	2.0
	1029	3.2
	1542	4.6
	1941	5.2
	2336	5.8
	2661	6.2
17.0	490	2.0
	1163	4.6
	1531	5.2
	1906	6.8
44.0	682	3.2
	782	3.9
	1170	6.2
	1197	6.2
	1235	6.2
	1332	6.8
	1332	6.8

*For design of these FSP's, see Figure A-1.

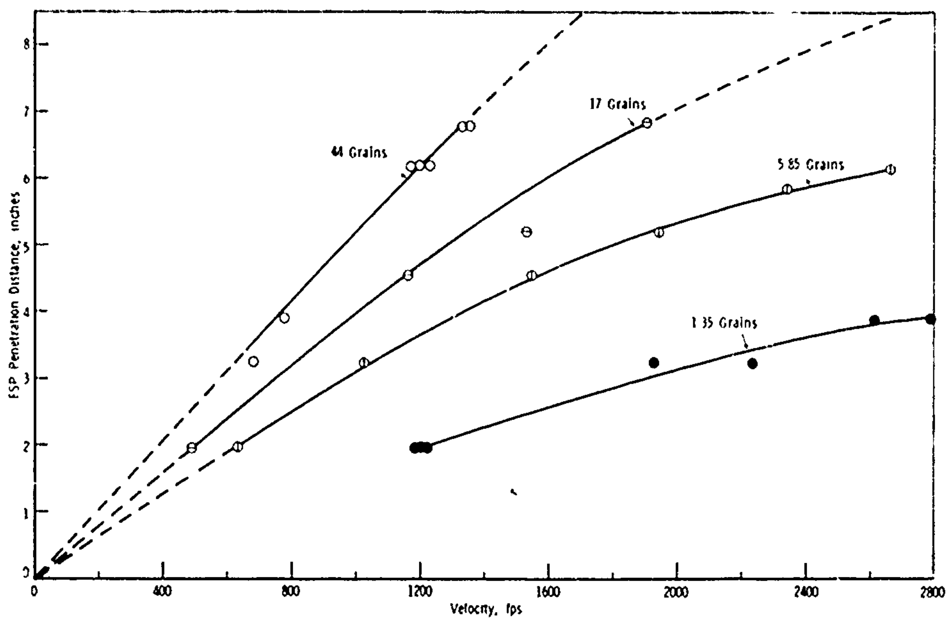

Figure A-2. Penetration of FSP's into stacked panels as a function of velocity.

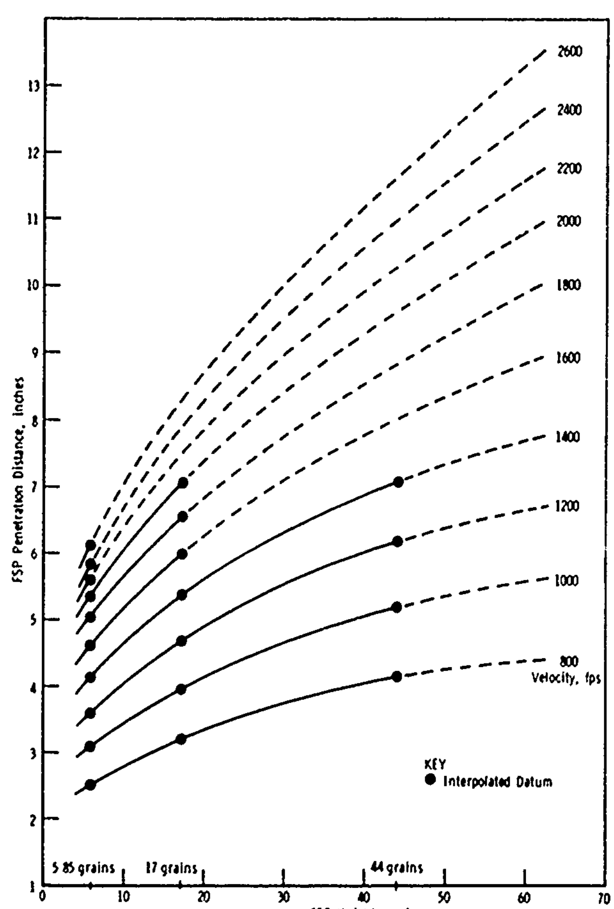

Figure A-3. Curves for estimating striking velocity of FSP on basis of penetration into stacked panels.

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Army Materials and Mechanics Research Center,
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SECONDARY DAMAGE TO AIRCRAFT BY RICOCHETED SMALL ARMS PROJECTILES AND FRAGMENTS -
Stuart V. Arnold and Russell G. Hardy

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